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TARGETING BMP PLACEMENT USING SWAT SEDIMENT YIELD ESTIMATES FOR FIELD-SCALE BMPS

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ABSTRACT

Soil erosion from agricultural fields is considered to be a significant contributor of sediment to surface waters in many watersheds across the United States. Black Kettle Creek subwatershed (7,818 ha) of Little Arkansas Watershed (360,000 ha) in south central Kansas was the focus of a innovative project to target conservation practice funding. The SWAT model was used with 10-m DEM topography, SSURGO soils, and a manually developed landuse/ land-cover layer. The calibrated model was used to identify the fields with greatest soil-erosion potential. Fields that had ephemeral gullies were identified by field reconnaissance and included for targeting. Various BMPs (no-till, conservation till, contour farming, terraces, contour grass strips, riparian buffers, and permanent grass), both singly and in selected combinations, were simulated and the effectiveness was determined. The mean BMP effectiveness ranged from 52% to 96% for single BMPs and 85% to 94% for selected combinations of BMPs. Permanent grass produced the greatest average single-BMP effectiveness (96%) followed by Terraces (with contour farming) (78%) and No-till (72%). No-till + Terrace (with contour farming) had the greatest combined-BMP effectiveness (94%). From these field-scale sediment-reduction estimates, payments to implement each BMP for a given field within the watershed were calculated. An in-field signup sheet was developed with field-specific sediment-loss-based payments calculated for each BMP option. This sheet served as a contract with the farmer/landowner for BMP implementation. The farmers/producers in this watershed chose the BMP to be implemented from the list of BMPs that and agreed to maintain the BMP for at least 5 years. The variability of sediment reduction results among fields demonstrated the important influence of site-specific conditions and simulation modeling in estimating soil-loss reductions possible with given BMPs.

KEYWORDS. Field Targeting, Critical Source Areas, Best Management Practices, Cost Effectiveness, Sediment Yields, SWAT, Calibration, ephemeral gullies

INTRODUCTION

Soil erosion from agricultural fields is considered to be a significant water quality concern in many watersheds across United States. Problems caused by soil erosion and sedimentation include loss of soil productivity in agricultural fields, water quality degradation in streams and reduced aquatic habitats.

The City of Wichita, the most populous city in Kansas, has undertaken a project to meet its growing water demands using the Equus Beds Aquifer Storage and Recovery (ASR) Project, which diverts water during high flows from the Little Arkansas Watershed through bank storage (diversion) wells. In 2007, there was approximately 1.3 million m^3 (350 million gal) of water injected into the Equus Beds Aquifer. However, for every 3,800 m^3 (1 million gal) of water injected, an average of 6.4 Mg (7 tons) of sediment needed to be removed prior to injection (Steele, 2006), representing a substantial treatment expense. Steele (2006) conducted a water-quality monitoring study and concluded that the Black Kettle Creek Subwatershed of Little Arkansas River Watershed delivered the greatest sediment yields compared to other subwatersheds (fig. 1). The current project was associated with a USDA-NRCS Conservation Innovation Grant (CIG), which had the goal of reducing sediment yields from Black Kettle Creek Watershed by

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cost-sharing implementation of targeted conservation practices in agricultural fields with greatest soil erosion potential.

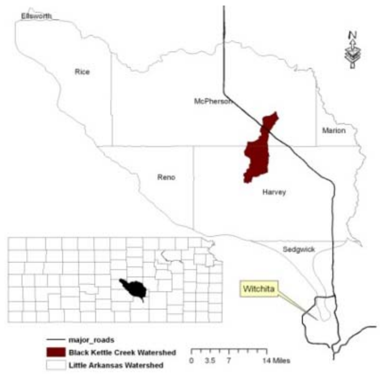

Figure 1. Little Arkansas Watershed and Black Kettle Creek Watershed.

The objectives of this study were to 1) Calibrate the SWAT watershed model and validate sediment-loss estimates from selected agricultural conservation practices; 2) Rank agricultural fields for potential soil erosion using a calibrated SWAT watershed model and rank the fields from most to least vulnerable for soil erosion; 3) Simulate and quantify the effectiveness of the BMPs; and 4) Design a farmer friendly in-field sign-up sheet that calculates field-specific payments.

Methods and Materials

The Soil and Water Assessment Tool (SWAT) Model

SWAT model was used to target the specific agricultural fields with greatest soil erosion potential and to quantify the effectiveness of BMPs. The SWAT model is a widely used, watershed-scale, process-based model developed by the USDA Agricultural Research Service (ARS) (Arnold et al., 1998; Neitsch et al., 2005; Gassman et al., 2007). The SWAT model is a distributed parameter, continuous scale model that operates on a daily time-step. The SWAT model divides the watershed into a number of subwatersheds based on topography. Each subwatershed is further divided into Hydrologic Response Units (HRUs), which are the smallest landscape component of SWAT used for computing the hydrologic processes. Flow, sediment, nutrients, bacteria yields are simulated at the HRU level, summed to the subwatershed level, and then routed through the channels, ponds, reservoirs and wetlands to the watershed outlet. The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) to estimate sediment yield at HRU level. The ArcSWAT 2.1.6 interface, which works on ArcGIS 9.2 platform, was used in this study.

Watershed Description and Model Inputs

Black Kettle Creek Watershed is a 7,818 ha (19,295 ac) subwatershed of Little Arkansas River Watershed located within McPherson and Harvey Counties in south-central Kansas (fig. 2). Primary land use in the watershed was cropland (84% of total area) followed by rangeland (12%), urban area (2%), and forests (2%). This watershed was dominated by wheat and other crops grown included sorghum, soybeans and corn. The major pollutant concerns in this watershed were sediment and phosphorus (Steele, 2006).

Daggupati et al. (2010) reported that extreme care was needed in selecting model input data when using SWAT for field-level targeting. In this study, maximum levels of detailed possible inputs were used to simulate the real time watershed conditions. Topographic data were derived using U.S. Geological Survey (USGS) 10 m × 10 m DEM (USGS, 1999). Soils data were derived from Soil Survey Geographic (SSURGO) database (USDA-NRCS, 2005). The SSURGO soil layer was prepared using SSURGO processing tool (Sheshukov et al., 2009) that converted SSURGO data to a format compatible with ArcSWAT. The Landuse/ Landcover (LULC) data were derived manually using the CLU (Common Landuse Unit or FSA) field boundary shapefile. Each field landcover was edited based on a field by field reconnaissance survey conducted in the watershed. The structural and non-structural management practices were derived from land surveys and aerial images. Details about farming operations, such as planting, harvesting, and manure application, were determined by consulting watershed specialists working in this watershed.

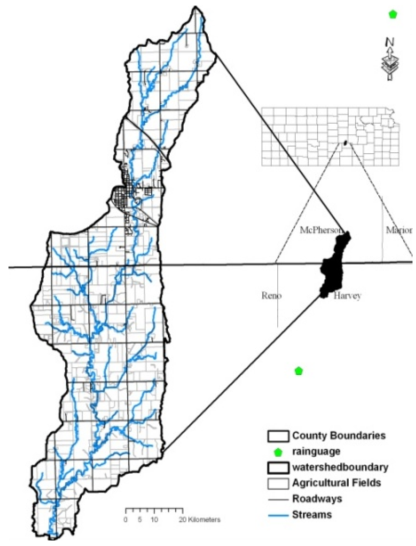

Figure 2. Black Kettle Creek Watershed.

Combinations of land cover, conservation structures, and tillage practices (e.g., wheat crop with terraces and conventional tillage) were created in the SWAT database by copying the data from its original land cover (e.g., wheat), and assigning a new land cover name (e.g., wheat with terrace) and crop code (CPNM) (e.g., TWHT). Extreme care was taken to prepare the LULC layer so that each field and its management practices was captured and represented spatially in the watershed. The daily precipitation and temperature data were derived from National Climate Data Center (NCDC) database for a time period of 01/01/1990 to 07/31/2009.

Measured flow and sediment data were collected from 01/01/2006 to 07/31/2009 at the outlet of Black Kettle Creek Watershed. Stream stage was recorded at 15-minute intervals using an automated stage recorder (ISCO 6700 water sampler, 730 bubbler flow module, Lincoln, NE) and averaged for each 24-hour period (midnight to midnight). Average daily water depth was used with surveyed stream cross-sectional area, surveyed longitudinal channel slope, and estimated channel roughness coefficient (Cowan, 1956) to estimate average daily streamflow using Manning's equation (Grant and Dawson, 2001). Stream total suspended sediment concentration was determined by filtration (Csuros, 1987) and converted to daily sediment mass using flow.

<u>SWAT Model Setup</u>

In the SWAT model, a minimum stream-definition area of 500 ha was used to define nine sub-basins within the watershed. Slope categories of 0-2%, 2-4%, and >4% were used to capture areas of low, medium and high slopes within the watershed. The HRUs in SWAT do not have spatial reference, however, this limitation can be overcome by redefining the topographic, soil and landuse thresholds to 0%, 0%, 0% (Gitau et al., 2004; Daggupati et al., 2010). This resulted in 1456 HRUs. The management practices (structural and non structural) and farming operations were represented in SWAT by modifying SWAT management files for each field within the watershed to model field-specific practices.

<u>Model Calibration and Evaluation</u>

Daily, monthly and yearly flow calibration was performed for the period from 01/01/2006 to 07/31/09 using daily measured stream flow recorded at the outlet of the watershed. An automated baseflow filter program (Arnold and Allen, 1999) was used to determine the baseflow contribution to the stream flow. Monthly and yearly sediment calibration was performed for the period from 01/01/2006 to 01/31/08 using measured sediment data. Daily calibration of sediment was not performed due to the lack of daily sediment data. During calibration, the model parameters were either increased or decreased from their respective baseline values based on the hydrographs and model efficiencies. The model was evaluated statistically using coefficient of determination (R^2), Nash-Sutcliffe model efficiency (NSE), percent bias (PBIAS), and root mean square error of observations to standard deviation ratio (RSR) (Moriasi et al., 2007) (Table 2).

Targeting fields with greatest soil erosion potential

Daggupati et al. (2010) reported that the SWAT HRU output needs to be converted to field level for practical targeting of BMP implementation. The calibrated SWAT model was run from 1996 to 2006 (12 year period) to get average annual sediment yields on HRU level. An ArcGIS based SWAT Targeting Toolbar (Daggupati et al., 2010) was used to convert the HRU-level output to field-level output to identify the fields with greatest soil-erosion potential. A total of 593 fields in the watershed were ranked from highest to the lowest on the basis of field-scale sediment yield density (Mg ha^{-1}). The top 20% of fields with the highest sediment yields (118 fields) were selected for preliminary targeting. A map of targeted fields was given to the watershed specialists working in the watershed. They visited the targeted fields and provided general validation of modeling predictions. However, they expressed their concern over model not identifying the fields with ephemeral gullies. Therefore, the fields with ephemeral gullies were manually identified. The watershed specialists invited the farmers/producers in the watershed who own the fields with greatest soil erosion potential and presented the modeling predictions. Farmers/ producers showed good interest and participated actively during the meeting.

BMP simulations and effectiveness

SWAT was successfully used to simulate the BMPs and evaluate the effectiveness of BMPs (Gitau et al., 2006; Parajuli et al., 2008; Tuppad et al., 2010). In this study, the effectiveness of various BMPs in the targeted fields was simulated using the calibrated SWAT model. Fields with its corresponding sediment yields as discussed in the earlier section was considered as a baseline. Selected BMPs were simulated for all the fields within the watershed that currently do not have a BMP using SWAT. A post processing tool was used to obtain the new sediment yields for all fields. The list of BMPs that were simulated is given in Table 1. The BMP effectiveness for each BMP for every field was calculated using

$$E\ \mathrm{BMP} = \frac{(\mathit{Baseline\ sediment\ yield} - \mathit{New\ BMP\ sediemnt\ yield})}{\mathit{Baseline\ sediment\ yield}} \times 100$$

Table 1. BMPs simulated.

Single BMPs	**Combinations of BMPs**
No-till	No-till + Contour farming
Conservation till	No-till + Terraces (+ Contour farming)
Contour farming	No-till + Contour grass strips
Terraces (+ Contour farming)	No-till + Riparian vegetative buffer
Contour grass strips	Conservation till + Contour farming
Riparian vegetative buffer strip (on contour)	Conservation till + Terraces (+ Contour farming)
Permanent grass	Conservation till + Contour grass strips
	Conservation till + Riparian vegetative buffer
	Contour grass strips + Riparian vegetative buffer strip

Cost Calculations

Our goal in this project was to give the money based on yield reductions using various new BMPs for every field that needs targeting and also to give a range of BMPs for farmers/ producers so that they can choose the best BMP that they can implement and maintain. Therefore, the payment for BMP implementation varied by field and by BMP chosen by the farmer/producer. The payment is mainly based on ton of sediment reduced by a particular BMP. The payment for a field to implement a particular BMP was calculated based on

$$\text{Payment for a field (\$)} = [\text{Baseline (t/ac)} - \text{BMP (t/ac)}] \times \text{Area (ac)} \times \$40\ (\$/\text{t})$$

The $40 value in the above equation is the amount that the project has decided to pay for each ton of sediment yield reduction. For example, a field of 3.5 ac produced a baseline sediment yield of 2.76 t/ac, and if the farmer of that field decided to implement the No-till practice, then the sediment yield after implementing No-till practice (based on simulated results for this field) is

1.04 t/ac. The payment that the farmer would receive for that field to implement No-till practice would be (2.76 – 1.04) t/ac × $40/t × 3.5 ac = $241.

In-field signup sheet

In-field signup sheets for each of the top 250 fields were created using a spreadsheet. The 250 fields were selected based on the ranked SWAT modeling results, and generally did not have conservation practices implemented currently. A database of baseline and BMP-simulated sediment yields for each of the 250 selected fields was created. On selecting the field number of interest, the values of field area (ac/field), estimated initial soil loss (t/ac), estimated new soil loss (t/ac) for each of the new BMP, and payment for each BMP ($/field) were generated automatically from the database. The developed in-field signup sheet was printed and given to the watershed specialists for their use in working with farmers of the targeted fields. The in-field signup sheet specified the exact amount of payment for each BMP for each specific field so that the farmer had clear choices in selecting the BMP for implementation.

RESULTS AND DISCUSSIONS

Model evaluation

Flow

The model was calibrated on daily, monthly and annual flow at the watershed outlet (table 3) and R^2, NSE, PBIAS and RSR were used to evaluate model predictions (table 2). The model performance was considered fair on daily time step based on R^2, NSE and RSR and excellent based on PBIAS. On monthly time step, the model performance was considered very good based on R^2 and RSR, good based on NSE, and excellent based on PBIAS. On yearly basis, the model performance was considered excellent based on R^2 and PBIAS and very good based NSE and RSR. Based on these statistics, the model was found to provide reasonable flow simulation.

Table 2. Model efficiencies for different pollutants (Parajuli et al., 2009).

Class	R^2, E Flow, sediment, TP	RSR Flow, sediment, TP	PBIAS Flow	PBIAS Sediment	PBIAS TP
Excellent	<0·90	0·00–0·25	$< \pm 10$	$< \pm 15$	$< \pm 25$
Very good	0·75–0·89	0·26–0·50	$\pm 11 \leq \pm 15$	$\pm 16 \leq \pm 30$	$\pm 26 \leq \pm 40$
Good	0·50–0·74	0·51–0·60	$\pm 16 \leq \pm 25$	$\pm 31 \leq \pm 50$	$\pm 41 \leq \pm 60$
Fair	0·25–0·49	0·61–0·70	$\pm 26 \leq \pm 30$	$\pm 51 \leq \pm 60$	$\pm 61 \leq \pm 70$
Poor	0·00–0·24	0·71–0·89	$\pm 31 \leq \pm 35$	$\pm 61 \leq \pm 70$	$\pm 71 \leq \pm 80$
Unsatisfactory	<0·00	>0·90	$\geq \pm 36$	$\geq \pm 71$	$\geq \pm 81$

R^2 = Coefficient of determination.
E = Nash sutcliffe efficiency index.
TP = Total phosphorus.
RSR = Root mean square error - observations standard deviation ratio.
PBIAS = Percent bias.

Table 3. R^2, NSE, PBIAS, RMSE, RSR for flow and sediment.

Constituent	Time step	R^2	NSE	PBIAS	RMSE	RSR
Flow	Daily	0.46	0.45	4.61	0.94	0.64
	Monthly	0.70	0.69	4.43	0.32	0.55
	Yearly	0.96	0.89	7.47	0.07	0.29
Sediment	Monthly	0.55	0.51	16.76	1.44	0.53
	Yearly	0.88	0.85	17.35	1.16	0.32

Sediment

The model was calibrated for monthly and yearly sediment yield at the watershed outlet (table 2, table 3). The model performance was considered good based on R^2, NSE and RSR and very good based on PBIAS. On yearly basis, the model performance was considered very good based on R^2, NSE, RSR and PBIAS. The model performance of the sediment was inferior to flow but considered sufficient for estimating sediment yields in this project.

<u>Field targeting</u>

The SWAT model and post-processing tools were used to derive the average annual sediment yields for each field within the watershed and the top 10 and 20% of fields with greatest soil erosion potential were identified (fig. 3). The identified fields (red colored fields) are frequently in close proximity to streams. Targeting these fields should provide more direct benefits than field’s further upslope and disconnected from streams so that the sediment transport is more efficient for closer fields. The fields in black color (fig. 3) had ephemeral gullies. These fields were manually recorded, as the SWAT model does not simulate ephemeral gully contributions. Few ephemeral gullies were seen in No-till fields; most occurred in row crop fields (Daggupati et al., 2010).

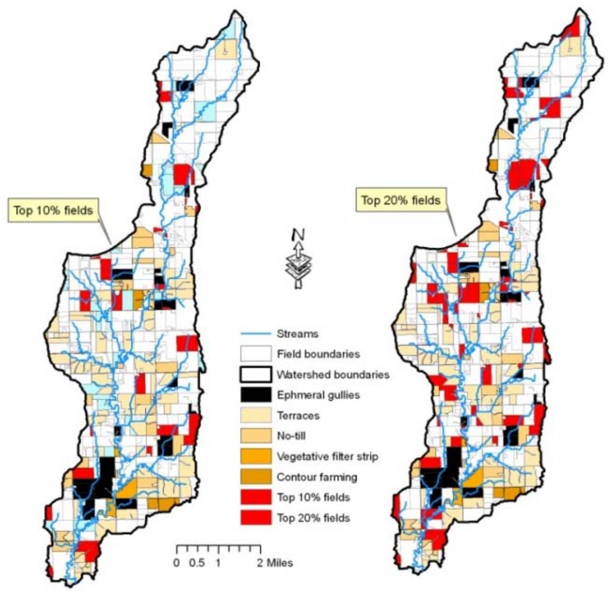

Figure 3. Top 10 and 20% targeting fields.

The modeled field level predictions were validated using published measurements of sediment yields from small cropland drainage areas in Kansas (Holland, 1971). According to Holland, cropland areas in the Black Kettle Creek Watershed area had sediment yields ranging from 0.46 to 0.91 Mg ha^{-1} yr^{-1} (1.24 to 2.48 ton ac^{-1} yr^{-1}). Before 1971, typical cropland areas in this region had minimal implementation of conservation practices and few terraces. Modeling results for the top 25 fields, also with no conservation practices or terraces, ranged from 0.42 to 0.83 Mg ha^{-1} yr^{-1} (1.14 to 2.26 ton ac^{-1} yr^{-1}), in good agreement with measured sediment yields. These results verified that the field level targeting conducted in this study provided realistic representation of sediment yields from actual fields supported the use of these modeling results for targeting.

<u>BMP effectiveness</u>

Various BMPs (both single and combined) were simulated and a database of top 250 fields with baseline sediment yield and each of BMP sediment yield for every field was created. The effectiveness of each BMP compared to the baseline was calculated (table 4). The mean BMP effectiveness of the single BMPs ranged from 52% to 96% while the mean BMP effectiveness for the combination of BMPs ranged from 85% to 94%. Permanent grass produced maximum mean BMP effectiveness in the single BMP category, while the No-till + Terraces (+ Contour farming) produced the greatest reductions in the combined-BMP category.

The effectiveness of each BMP varied by field (table 4). For example, No-till BMP had a mean effectiveness of 72% with a range of 59% to 81% among 250 fields. Similar variability was seen for all BMPs simulated in this study. Model predictions captured the unique, variable soil, slope and landuse conditions present on each field that interacted with each BMP to produce a given sediment-reduction result. This result demonstrated the importance of using field-specific modeling results for field targeting instead of generalized percent reductions for given practices.

Table 4. Statistics of yield reductions for simulated BMPs for top 250 fields with highest sediment yields

BMPs	Min	Max	Mean	Median	Stdev
No-till	59%	81%	72%	72%	5%
Conservation till	42%	67%	52%	51%	5%
Contour farming	45%	68%	53%	53%	2%
Terraces (+ Contour farming)	70%	87%	78%	78%	2%
Contour grass strips	54%	69%	61%	62%	1%
Riparian vegetative buffer strip (on contour)	62%	63%	62%	62%	0%
Permanent grass	95%	100%	96%	96%	1%
No-till + Contour farming	76%	92%	87%	87%	2%
No-till + Terraces (+ Contour farming)	80%	98%	94%	95%	3%
No-till + Contour grass strips	85%	96%	93%	94%	2%
No-till + Riparian vegetative buffer	76%	92%	87%	87%	2%
Conservation till + Contour farming	75%	90%	85%	84%	2%
Conservation till + Terraces (+ Contour farming)	70%	91%	88%	88%	3%
Conservation till + Contour grass strips	85%	91%	87%	87%	1%
Conservation till + Riparian vegetative buffer	67%	89%	85%	86%	3%
Contour grass strips + Riparian vegetative buffer strip	76%	92%	87%	87%	2%

Standard deviations were less than 5% for all the BMPs simulated (table 4). This shows that a majority of fields perform within a reasonably small range of sediment yield reductions. However, field targeting attempts to identify the field with the greatest benefits of implementation, not the average benefits. The differences between mean and maximum reductions for a given BMP were typically 1.5 to 4.5 times greater than the standard deviation. Again, this demonstrates the value of using modeling results to identify these fields with the greatest potential for impact.

CONCLUSIONS

The SWAT model was used successfully to identify the agricultural fields with greatest sediment potential in the Black Kettle Creek Watershed. The model was calibrated for flow and sediment to assure and field-level sediment yields were validated with the historic local data. Fields that had ephemeral gullies were identified manually and were included for targeting, as the SWAT model cannot identify ephemeral gullies. Various BMPs (single and combined) were simulated for each field and their effectiveness was calculated. The effectiveness of a particular BMP was different for each field based on its unique combinations of slope, soil and existing landuse. Payment to implement each BMP for a given field was calculated. An in-field signup sheet was developed to facilitate farmer signup for BMP implementation for each of the selected fields. The variability of sediment reduction results among fields demonstrated the important influence of site-specific conditions in estimating soil-loss reductions possible with given BMPs. Simulation models are needed to identify the fields having the greatest potential for sediment-loss reduction, which is the basis of effective BMP targeting. In this study, the model was also used successfully to quantify sediment-loss reductions as a basis for conservation practice payment structure. We anticipate that a system that ties payments directly to sediment-loss-reduction estimates will be effective in producing measureable improvements in stream sediment quality; future work based on pre- and post-implementation in-stream monitoring data will test this hypothesis.

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